ASTR-1020: Astronomy II
Course Lecture Notes
Section VI

Dr. Donald G. Luttermoser
East Tennessee State University

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Abstract

These class notes are designed for use of the instructor and students of the course ASTR-1020: Astronomy II at East Tennessee State University.

VI. Stellar Evolution: Mid-Life and Old Age

A. Life on the Main Sequence

1. All main sequence stars are powered by H→He thermonuclear reactions in their cores (see §II.C of these notes) $\Longrightarrow$ *hydrogen-core burners.*

2. Two types of reaction chains occur in main sequence stars.

a) Proton-proton (p-p) chain for stars with $M < 2M_\odot$.

b) CNO cycle for $M > 2M_\odot$. This cycle only occurs in bigger stars (even though it is more efficient than p-p) because the core temperatures have to be high enough for ^{1}H to overcome ^{12}C electrostatic repulsion.

3. Laws of Stellar Structure.

a) **Hydrostatic equilibrium** (HSE).

i) The weight of each layer is balanced by the gas pressure in that layer.

ii) Acts like a pressure-gravity thermostat $\Longrightarrow$ internal pressure and gravity must balance throughout the star.

iii) Keeps the star stable.

b) **Thermal equilibrium** (TE).

i) Energy into a layer = energy out of a layer.

ii) Luminosity of a star is balanced by nuclear energy generation in the core.

iii) Keeps the star shining.

c) **Energy transport**.

i) Energy flows from hot to cool regions in the most efficient means possible.

ii) Transport modes: radiation, convection, and conduction (which is only important in white dwarfs and stellar coronae).

iii) The **opacity** (resistance to radiation flow) of the gas determines which one of these is most efficient.

d) With these laws, we can build stellar models.

4. Main Sequence Lifetimes.

a) ZAMS (Zero Age Main Sequence) defines the region on the H-R diagram when a star first starts burning H in its core.

b) The luminosity on the main sequence scales as mass raised to the 4th power:

$$\frac{L}{L_\odot} = \left(\frac{M}{M_\odot}\right)^4 . \qquad \text{(VI-1)}$$

$\Longrightarrow$ a small increase in mass corresponds to a large increase in luminosity.

c) This means that main sequence stars burn their fuel (*i.e.*, H) at an ever increasing rate with mass. This is due to the large increase in central temperatures as mass increases $\Longrightarrow T_{c\odot} = 1.5 \times 10^7$ K.

d) A star will stay on the main sequence only as long as its fuel remains $\Longrightarrow$ Lifetime:

$$t_{\rm ms} = \frac{\rm fuel}{\rm rate\ of\ consumption} \propto \frac{M}{L} \propto \frac{M}{M^4} \propto \frac{1}{M^3} \quad \text{(VI-2)}$$

(note that the "$\propto$" symbol means "proportional to"), in terms of the Sun:

$$t_{\rm ms} = \left(\frac{M_\odot}{M}\right)^3 \times 10^{10}\ {\rm yr}, \quad \text{(VI-3)}$$

since the Sun main sequence lifetime is 10^{10} yrs.

If $M = 10\,M_\odot \Longrightarrow t_{\rm ms} = 1.0 \times 10^7$ yrs.

5. Main Sequence Interior Structure.

a) High mass stars ($M > 2\,M_\odot \sim$ F0 V) have convective cores and radiative envelopes.

b) Low mass stars ($0.4\,M_\odot < M < 2\,M_\odot$) have radiative cores and convective envelopes.

c) Very low mass stars ($M < 0.4\,M_\odot \sim$ M4 V) are completely convective.

6. These internal structure characteristics have a major impact on stellar atmospheres.

a) As we recall from our study of the Sun, the heated regions of the outer solar atmosphere, the chromosphere and corona, are generated from sound waves and magnetic waves produced in the convection zone of the outermost interior region of the Sun.

b) This is why stellar chromospheres and coronae are only seen in cooler main sequence stars (F, G, K, and M) and not the hotter main sequence stars, since only the cooler lower mass main sequence stars have interior convection zones near the surface of the star.

7. Masses.

a) The high mass limit on the main sequence is about 50 $M_\odot$ (O5 V). This (approximate) high-mass limit is set due the following conditions:

i) Gravitational instabilities during collapse typically break apart protostars larger than 50 $M_\odot$.

ii) If stellar mass objects greater than 50 $M_\odot$ do survive gravitational instabilities during birth, these objects would collapse very rapidly from protostar state and burn their thermonuclear fuel so quickly (*i.e.*, within 10 million years) that few of these objects would be seen. When these hypermassive stars do die, they have either of the following two fates:

- Supernova and leave either a massive ($M \sim 3\ M_\odot$) neutron star or a black hole.
- Collapse directly to a black hole without exploding.

b) The low mass limit is about $0.08\, M_\odot$ (M8 – M10 V).

i) Temperatures never get high enough to ignite H.

ii) Objects with $M < 0.08\, M_\odot$ are called **brown dwarfs**. Three new spectral classes have been invented for brown dwarfs:

- Spectral class **L**: These objects have strong metal hydride bands (FeH, CrH, MgH, CaH) and prominent alkali lines (Na I, K I, Cs I, Rb I) and range in temperature from 2200 K down to approximately 1200 K. As of April 2005, over 400 L dwarfs have been identified.

- Spectral class **T**: Whereas near-infrared (NIR) spectra of L dwarfs show strong absorption bands of H_2O and carbon monoxide (CO), the NIR spectrum of T dwarfs are dominated by absorption bands from methane (CH_4). In addition, the metal hydride bands seen at optical wavelengths in L dwarfs are weak or absent in T dwarfs. These objects range in temperature from approximately 1200 K down to approximately 700 K. As of April 2005, 58 T dwarfs have been identified.

- Spectral class **Y**: These ultra-cool brown dwarfs have temperatures less than 700 K and have strong bands of ammonia (NH_3) seen at NIR wavelengths. So far, only one Y dwarf has been discovered.

iii) These *failed stars* are distinguished from red dwarf stars (spectral class M) through the appearance of lithium (Li) in their spectra which is not seen in the low-mass M stars.

- The high temperatures found at the center of normal stars supports hydrogen fusion.

- Lithium is rapidly depleted under these high temperatures. This occurs by a collision of Lithium-7 and a proton producing two Helium-4 nuclei. The temperature necessary for this reaction is just below the temperature necessary for hydrogen fusion.

- Convection in low-mass stars ensures that lithium in the whole volume of the star is depleted. Therefore, the presence of the lithium line in a candidate brown dwarf's spectrum is a strong indicator that it is indeed substellar.

- However, lithium is also seen in very young stars, which have not yet had a chance to burn it off. Very young low-mass stars can be distinguished from brown dwarfs by the chromospheric activity seen in the spectra of these low-mass M stars.

- Heavier stars like our Sun can retain lithium in their outer atmospheres due to the fact that the convection zone of these stars do not extend very deep into the star and these outer layers never get hot enough to deplete lithium through fusion. However these stars are easily distinguishable from brown dwarfs by their temperatures.

- Note that brown dwarfs at the high end of their mass range can be hot enough to deplete their lithium when they are young. Dwarfs of mass greater than 65 $M_{\rm Jupiter}$ can burn off their lithium by the time they are half a billion years old, thus this test is not perfect.

iv) Objects with $M < 10\,M_{\rm Jupiter}$ ($= 0.01\,M_\odot$) are called planets. Note however that it is sometime difficult to distinguish whether an object should be classified as a planet or a brown dwarf.

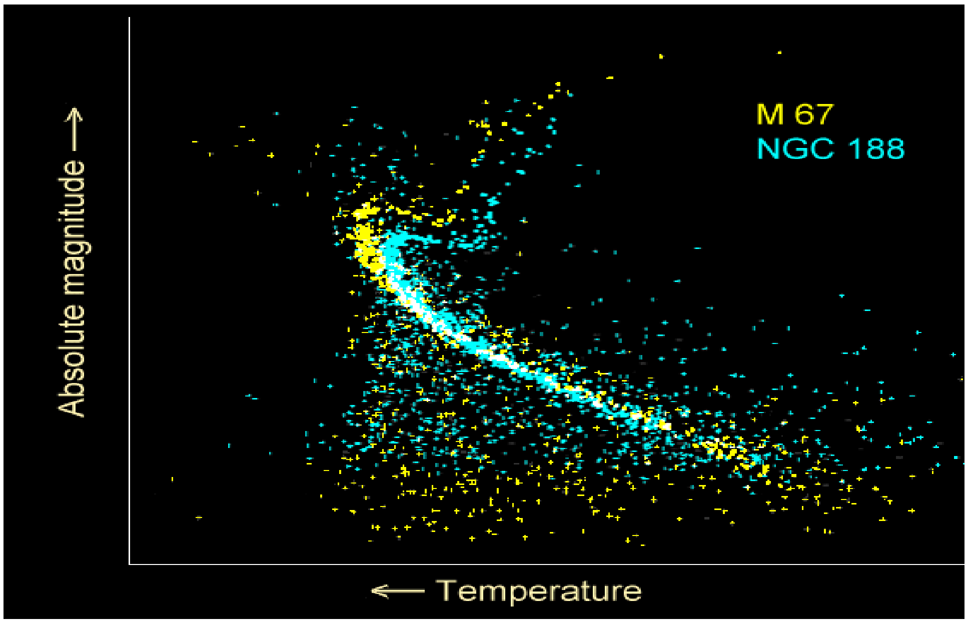
c) Main sequence stars (actually any star) continuously lose mass due to a stellar wind.

i) In the case of massive hot stars (O and B stars), absorption of photospheric photons by hydrogen and helium absorption lines drive the stellar wind $\Longrightarrow$ **radiatively driven winds** by line opacity. These stars typically lose between $10^{-6} M_\odot$/yr to $10^{-4} M_\odot$/yr.

ii) The stellar wind of lower-mass coronal stars results from the corona being hot and the thermal velocity of the gas exceeding the escape velocity from the star. In these stars the mass is lose in regions of the corona where the magnetic field does not close on itself (regions called **coronal holes**) $\Longrightarrow$ **thermally driven winds**. These stars typically lose between $10^{-15} M_\odot$/yr to $10^{-13} M_\odot$/yr.

iii) Very cool red giant and supergiant stars lose mass through momentum exchange of photospheric photons on dust in the atmosphere $\Longrightarrow$ **radiatively driven winds** by dust opacity. These stars typically lose between $10^{-8} M_\odot$/yr to $10^{-6} M_\odot$/yr.

8. Much of what we know of stellar evolution comes from the study of the H-R diagrams of star clusters. For instance, the age of a star cluster can be determined by locating the **main sequence turn-off** position.



The figure above shows the Hertzsprung-Russell diagrams for two open clusters. NGC 188 (blue) is older, and shows a lower turn off from the main sequence than that seen in M67 (yellow).

Example VI–1. An O5 V star has a luminosity of $10^7\ L_\odot$, a A0 V star, $80\ L_\odot$, and an M0 V star, a luminosity of $0.1\ L_\odot$. What is the mass and main sequence lifetime of each star?

Rewriting Eq. (VI-1):

$$\frac{M}{M_\odot} = \left(\frac{L}{L_\odot}\right)^{1/4},$$

Then

$$M_{\rm O5} = \left(\frac{10^7 L_\odot}{L_\odot}\right)^{0.25} M_\odot = 56\, M_\odot$$

$$M_{\rm A0} = \left(\frac{80 L_\odot}{L_\odot}\right)^{0.25} M_\odot = 3.0\, M_\odot$$

$$M_{\rm M0} \;=\; \left(\frac{0.1L_\odot}{L_\odot}\right)^{0.25} M_\odot = 0.56\,M_\odot.$$

From Eq. (VI-3) the main sequence lifetimes are:

$$\begin{aligned} t_{\rm ms}({\rm O5}) &= \left(\frac{M_\odot}{56M_\odot}\right)^3 \times 10^{10}\ {\rm yr}\ = 5.7\times 10^4\ {\rm yr} \\ t_{\rm ms}({\rm A0}) &= \left(\frac{M_\odot}{3.0M_\odot}\right)^3 \times 10^{10}\ {\rm yr}\ = 3.7\times 10^8\ {\rm yr} \\ t_{\rm ms}({\rm M0}) &= \left(\frac{M_\odot}{0.56M_\odot}\right)^3 \times 10^{10}\ {\rm yr}\ = 5.7\times 10^{10}\ {\rm yr}. \end{aligned}$$

As you can see, the most luminous stars in the Galaxy only remain on the main sequence for 57 thousand years, whereas a star like Vega (A0 V) will remain for 370 million years (Vega is relatively young), and an M0 V star will remain on the main sequence for 57 billion years! Since the Universe is about 12-14 billion years old, no M0 star has yet evolved off of the main sequence.

B. Evolution off of the Main Sequence.

1. A star spends 90% of its life (white dwarfs, neutron stars, and black holes are stellar death) on the main sequence.

2. When H in the core is depleted:

a) Only He ash is left.

b) Core goes out of TE and HSE and contracts.

3. This contraction heats the core (though initially not enough to start He fusion) and also heats the H-rich shell just above it.

a) H fusion starts in that shell.

b) H-shell burning.

4. This H-shell burning increases the energy input into the outer envelope.

a) Causes the envelope to expand.

b) As it expands, it cools $\Longrightarrow$ producing a **red giant star**.

C. The Red Giant Phase.

1. Helium (He) will not fuse until $T > 10^8$ K.

a) H fuses at $T > 10^7$ K.

b) He fuses via the **triple-alpha process**

$$\left.\begin{array}{lcl} {}^4\text{He} + {}^4\text{He} & \longrightarrow & {}^8\text{Be} + \gamma \\ {}^8\text{Be} + {}^4\text{He} & \longrightarrow & {}^{12}\text{C} + \gamma \end{array}\right\} \text{3 alpha particles (He)} \longrightarrow \text{1 carbon atom.}$$

Besides these two reactions, the following reaction can also occur

$$^{12}\text{C} + {}^4\text{He} \longrightarrow {}^{16}\text{O} + \gamma$$

$$\begin{array}{rcl} {}^4\text{He} & = & \text{helium nucleus = alpha particle (2p, 2n)} \\ {}^8\text{Be} & = & \text{beryllium (4p, 4n)} \\ {}^{12}\text{C} & = & \text{carbon (6p, 6n)} \\ {}^{16}\text{O} & = & \text{oxygen (8p, 8n)} \\ \gamma & = & \text{gamma ray photon} \end{array}$$

c) The carbon and oxygen atoms from which we are made were created through these reaction chains $\Longrightarrow$ we owe our existence to an ancient red giant star that no longer exists — **We are star stuff!**

d) The names "alpha" (α), "beta" (β), and "gamma" (γ) particles were invented by the scientists who first did experiments with radioactivity. Particles that were given off by radioactive elements were initially unidentified.

i) *Alpha* particles are positively charged particles. These particles turned out to actually be the nuclei of helium (He) atoms.

ii) *Beta* particles are negatively charged particles. These particles were later identified as electrons.

iii) *Gamma* particles have no charge and are actually high energy (*i.e.*, short wavelength) photons $\Longrightarrow$ gamma ray photons.

2. Stars with $M < 0.4\,M_\odot$ are completely convective on the main sequence and never develop an inert He core — and they never get hot enough to fuse helium.

3. Stars $0.4\,M_\odot < M < 4\,M_\odot$ ignite He in a degenerate core $\Longrightarrow$ **Helium Flash**.

a) Electron degeneracy: free e^- squeezed so close together that the Pauli Exclusion Principle takes effect (2 electrons cannot exist in the same state) — degeneracy pressure counterbalances gravity, hence resists compression.

b) Pressure (P) in a degenerate gas is independent of temperature.

c) The temperature of the He atoms continues to rise as matter is dumped from the H-burning shell above — but pressure remains constant

$\Longrightarrow$ normal pressure-temperature-gravity thermostat is off.

d) T reaches 10^8 K so He starts fusing which increases T more (without increasing P) $\Longrightarrow$ increase of T increases reaction rates, which further increases T!

$\Longrightarrow$ runaway thermonuclear reactions

$\Longrightarrow$ **Helium Flash**.

e) Soon, T gets high enough to lift degeneracy $\Longrightarrow$ HSE is reinstated $\Longrightarrow$ red giant becomes stable (*i.e.*, a **red giant clump star**).

4. Stars greater than 4 $M_\odot$ burn He in a gradual manner — no runaway, hence no flash.

5. After He is used up, more massive stars can fuse heavier elements.

D. Russell-Vogt Theorem.

1. Despite the range of stellar luminosities, temperatures and luminosities, there is one unifying physical parameter $\Longrightarrow$ the **mass of the star**.

a) Hot, bright stars are typically high in mass.

b) Faint, cool stars are typically low in mass.

c) This sole dependence on mass is so strong that it is given a special name, the **Russell-Vogt Theorem**.

2. Though not as important as mass, the **composition** plays a secondary role of the observational characteristics of a star. This secondary role of "composition" is often included in the Russell-Vogt Theorem.

3. In summary, the Russell-Vogt Theorem states that all the parameters of a star (its spectral type, luminosity, size, radius and temperature) are determined primarily by its mass and secondarily by its composition.